LONGITUDINAL COUPLED-BUNCH OSCILLATIONS IN THE RECYCLER RING

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PURPOSE

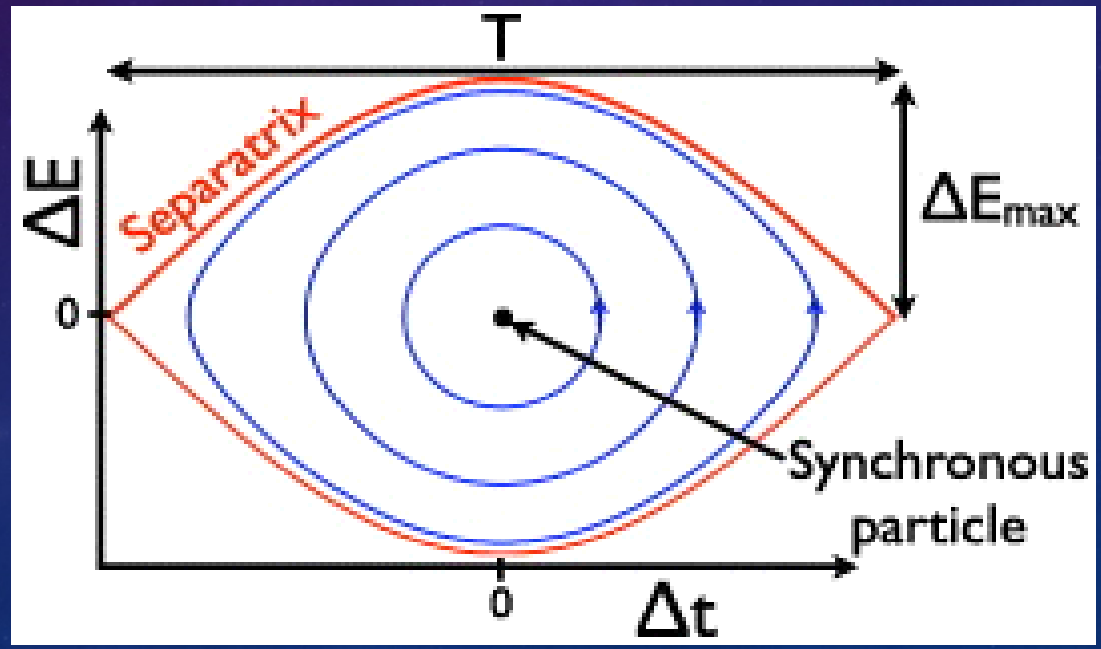
- Measure the Shunt Impedance of the Higher Order Modes (HOMs) of our cavity
- Measure the coupled bunched motion in our cavity
- Measure the effectiveness of the dampers on the 154 MHz mode

ACCELERATOR PHYSICS

- Particles are accelerated in “bunches” of approximately 10^{13} particles
- Particles undergo acceleration inside of a synchrotron, hitting a waveform with f = 52.809 MHz every rotation
- There are 588 bunches in the Recycler Ring
- Further divided into 7 batches with 84 bunches each
  - Our purposes: 1 batch with 84 bunches; 82 bunches with particles and 2 empty bunches. The other 6 batches are empty
  - Typically: 6 of the above batches described with one empty batch. This empty batch is used for “slip stacking”

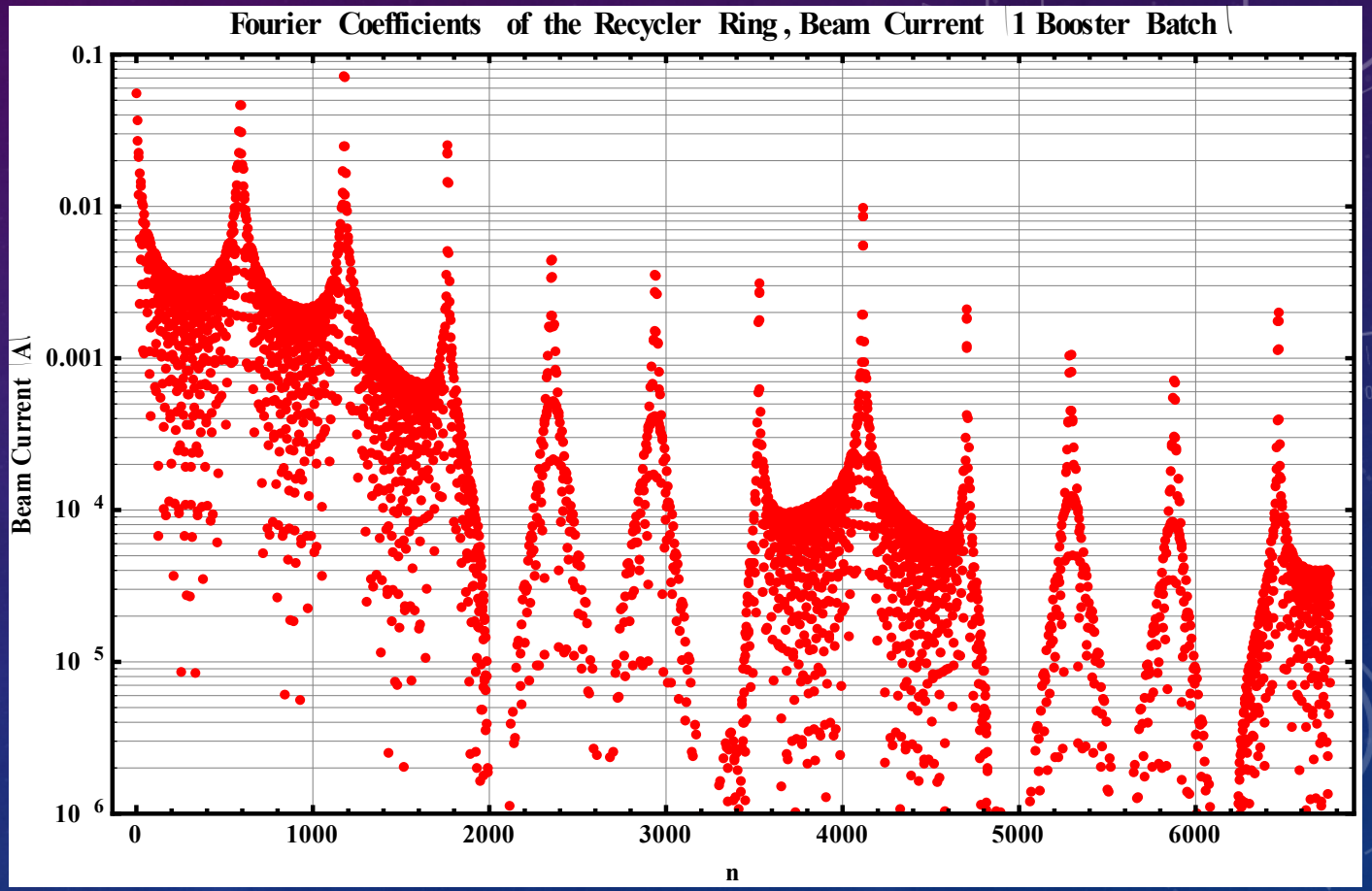
SEPARATRIX

- Separatrix is a “region of stability” (pictured below)
- Particles in a bunch have varying energies and frequencies
  - Reaching the waveform earlier = losing energy, reaches later on next cycle
  - Reaching later = gaining energy, reaches earlier on next cycle
  - Reaching exactly the right time = the ideal particle, “synchronous particle”
  - Particles outside of this region are separated from the bunch



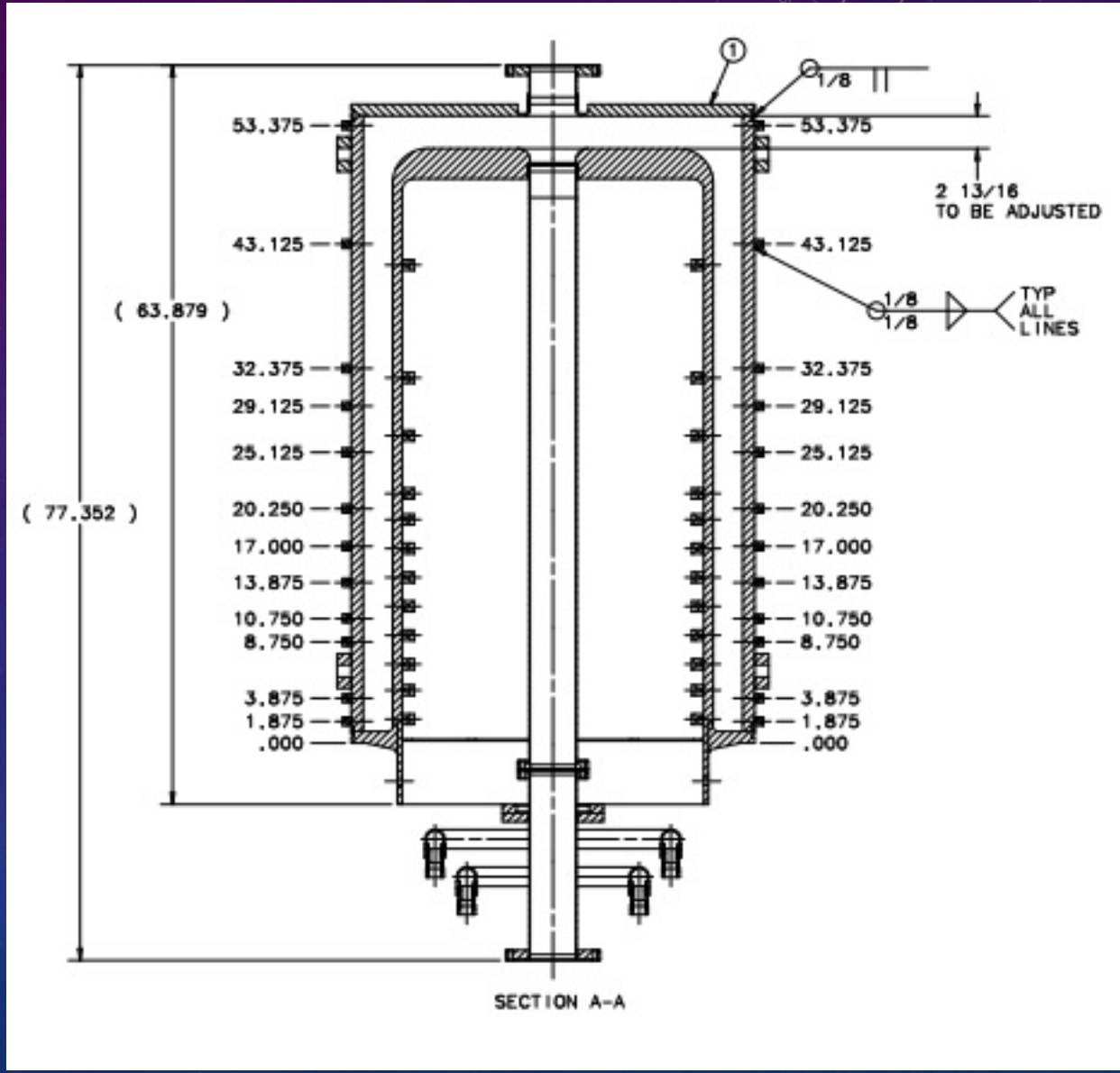
MODELING PULSES

- Can be modeled as parabolas separated by approximately 18.9 seconds in time (52.809 MHz)
- Normalized to 82⁄588 A current when taking the area under all pulses
- 4 ns base width
- A Fourier decomposition can be taken to find values of current at each of the harmonic frequencies (odd multiples of 52.809 MHz) for the entire set of 7 batches
- Values of Fourier Coefficients as a function of a harmonic number (integer multiples of 1⁄588) shown to the right in a log-log plot



OUR CAVITY

- Schematic of our cavity to the right
- Inner radius of 13.5”, outer radius of 16”
- Length of 53”
- Boundary conditions require a wave solution where it is zero at the top (shorted end) and maximum at the bottom
- Solutions require periodic functions with odd integer multiples of quarter wavelengths with f = 52.809 MHz
- These solutions are known as the “Higher Order Modes” (HOMs)



IDENTIFICATION OF HOM (HIGHER ORDER MODES)

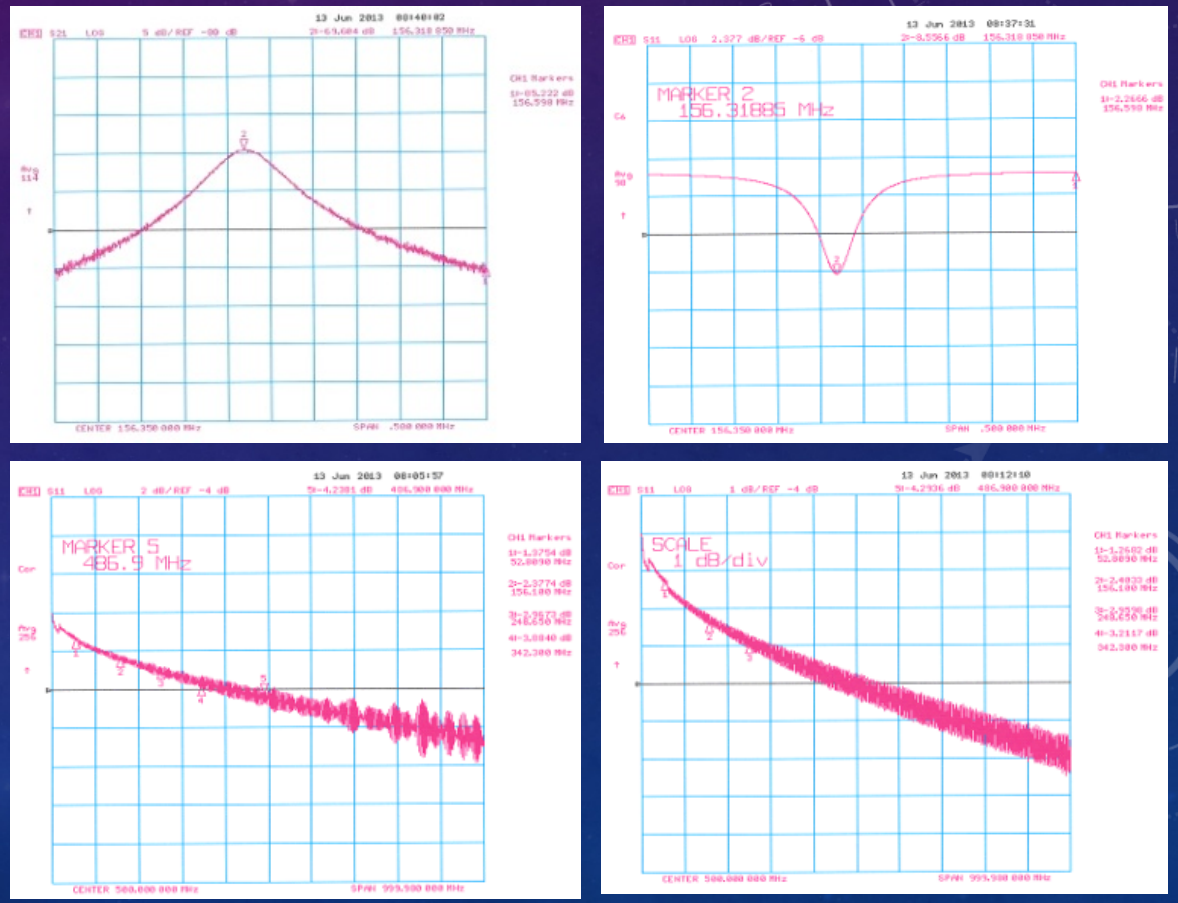
- Measurements taken using an Agilent 8753ES S-Parameter Network Analyzer
- Measurements of Quality factor, phase, and loss were taken two different gap monitors at the MI-60 building
- If those parameters matched up then we have identified a harmonic frequency
- Other HOMs exist in the system, due to other reasons. These modes include Ring Modes and Coaxial/Power Amplifier Modes. These do **not** match up in phase or loss
- HOMs measured were the following frequencies (in MHz): **52.809; 154.063; 247.595; 336.365; 475.141; 543.506**

IDENTIFICATION OF TEM MODES (CONT.)

- Similar phase, amplitude, and quality factor are required due to propagation of other modes parallel to the circular detector
- The harmonic frequencies will line up with the detectors at equal phases
- Ring modes and coaxial modes propagate perpendicular to the harmonic modes
- Therefore they land at the detectors at different phases, therefore they will be measured in both gap monitors but they will not have the same values
- Other TEM modes will exist in both gap monitors but they aren’t HOMs

HOMS CONTINUED

- Cavity is in the recycler ring and has a certain amount of response associated with each mode
- Shunt impedance - a characteristic resistance associated with each of the HOMs
- Equation for shunt impedance depends on the inverse of the square root of the harmonic number and the shunt impedance for the fundamental (as well as various other factors)
- Shunt impedance was calculated both theoretically and through measurements (right)
- They are TEM modes (Transverse Electromagnetic)



SHUNT IMPEDANCE DATA TABLE

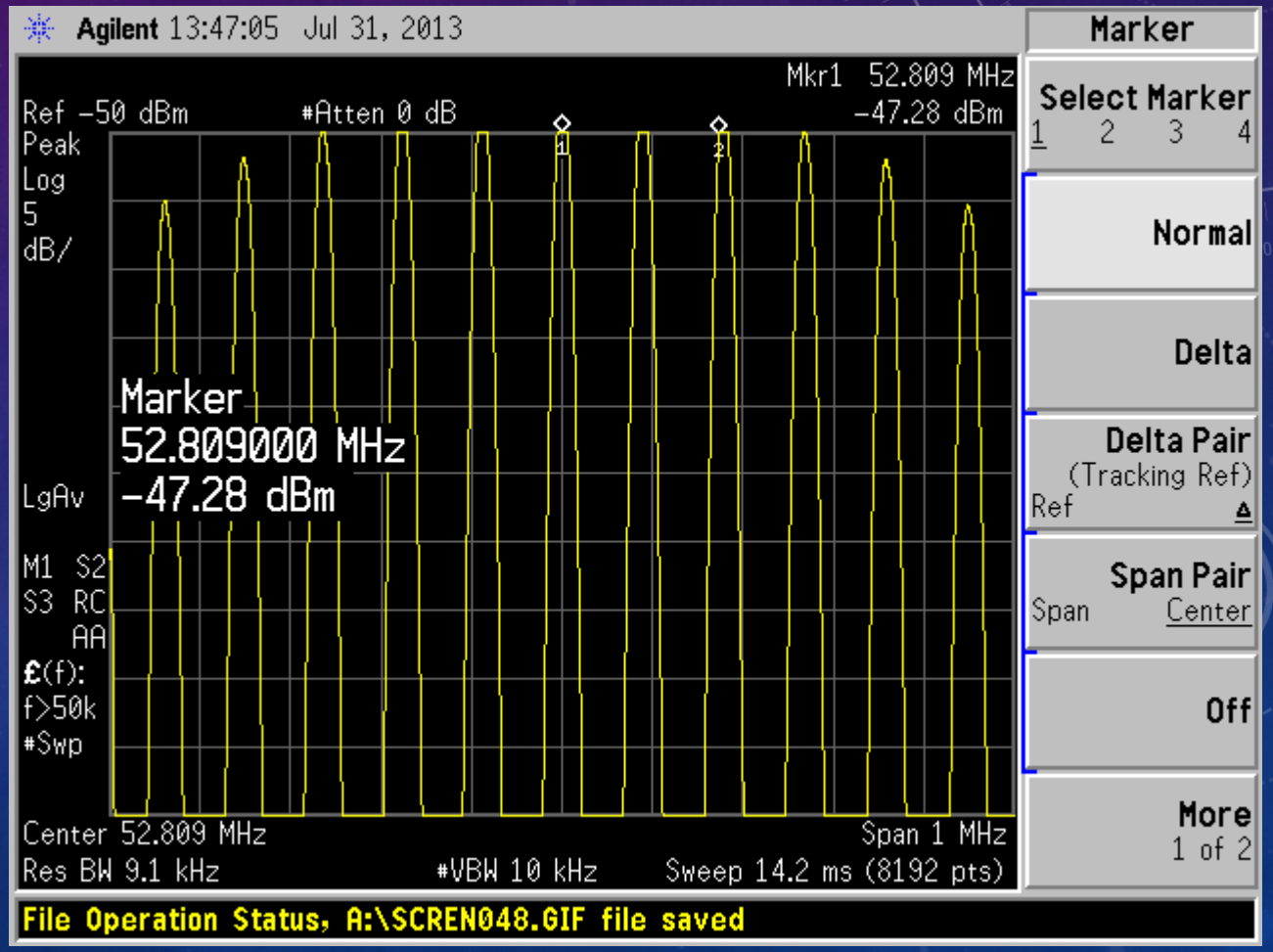
- Our measurement device includes a Magnetically Coupled Loop and Capacitative Pickup that displays 1 Volt for every 89.5 kV measured at 52.809 MHz
- This was modeled as a resistor and capacitor in series (which would both have a total voltage drop of 1 V) with a capacitor in parallel to both (with a total voltage drop of 89.5 V) to adjust for different frequencies
- Dampers applied to the 3rd harmonic compared to no dampers
- Theoretical values calculated using this equation:

$$R_{shunt} = \frac{2\mu_0\sqrt{\frac{\sigma f}{\pi^3 \epsilon_0}}\,\mathrm{Log}\left[\frac{r_2}{r_1}\right]^2}{\left(\frac{1}{r_1}+\frac{1}{r_2}\right)+\frac{1}{\ell\left(\frac{1}{4}-\frac{1}{\pi^2}\right)}\mathrm{Log}\left[\frac{r_2}{r_1}\right]}$$

Frequency (MHz)	Theoretical (kΩ)	Experimental (kΩ)
52.809	77.8	75.8
154.063	45.0	20.4 (uda)/2.45 (da)
247.595	34.9	5.8
336.365	29.5	22.5
475.141	26.0	21.3
543.506	23.5	2.6

VOLTAGE VALUES AND COUPLED BUNCHED MOTION

- Measurements taken by a Agilent 8753S S-Parameter Spectrum Analyzer operating at -12 dB, 16 ns cable, 1 Ω
- Measurement result at the right; took that value of loss in dBm and converted it to power in Watts
- Multiplied by 100 (2*50 due to a 50 Ω load resistor) then divided by 1 Ω to receive current
- Multiplied current by shunt impedance to receive the voltage loss at each HOM



ADDITIONAL NOTES

- Normalized all measured values so that the fundamental had 1 Amp of current (because we had only 5.4 mA of current going through both theoretically and experimentally
- This required us to multiply all experimental values by around 200 (current measured @52.809 is .0054 mA) and theoretical values by around 4 (current predicted @52.809 is .25 mA)
- Results in table on the right

Frequency (MHz)	Predicted (V)	Measured (V)
52.809	77800	77800
154.063	1504.0	65.5641
247.595	899.43	35.7079
336.365	1720.2	110.582
475.141	1263.1	1372.08
543.708	56.852	14.2224

CONCLUSIONS

- There is very little voltage drop in the 154 MHz mode, meaning that it is heavily damped (and the 5^{th} and 7^{th} harmonics are also very highly damped)
- The shunt impedances are in reasonable agreement between theory and experiment for all but the 11^{th} harmonic and the 3^{rd} and 5^{th} harmonic
- The voltage values are in disagreement in the 7^{th} harmonic, meaning there is additional damping in that particular harmonic
- Many of the losses in the beam occur in the fundamental

FURTHER STUDY

- Taking measurements more often for consistency due to drift in frequencies and various values
- Being able to introduce beam more often operating at the voltage we obtained
- Identifying some of the other modes we have measured

ACKNOWLEDGEMENTS

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QUESTIONS?